

Four-Quark Mesons

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Abstract. The features of a model interpreting the light scalar mesons as diquark-antidiquark bound states and the consequences of its natural extension to include heavy quarks are briefly reviewed.

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The $q\bar{q}$ assignment has never really worked for the scalar mesons below 1 GeV. Alternative identifications have been proposed in the past [1], notably the f as a bound $K\bar{K}$ molecule [2] or as a $(q)^2(\bar{q})^2$ state [3]. We illustrate in this contribution the hypothesis, examined in Ref. [4], that the lowest lying scalar mesons are S -wave bound states of a diquark-antidiquark pair. Following Ref. [5], the diquark is more likely bound in the $\bar{\mathbf{3}}_c, \mathbf{0}_s$ (color antitriplet, spin zero) channel. If strange quarks are included, Fermi statistics favors the $\bar{\mathbf{3}}_f$ combination. Therefore $(q)^2(\bar{q})^2$ states form a flavor $SU(3)$ nonet. We propose to put the $\sigma(450)$ [6] in the $I = S = 0$ state, and to assign to the $S = \pm 1$ states the $\kappa(800)$, a $K\pi$ resonance seen by several experiments, most recently in the $K\pi\pi$ spectrum from D decays [7]. A simple hypothesis on the way the $(q)^2(\bar{q})^2$ states may transform into a pair of pseudo-scalar mesons is found to give a rather good one-parameter description of the decays allowed by the OZI rule [8]. The extension of the picture to states including one or more heavy quarks gives quite interesting predictions, accommodating recently discovered narrow states.

Quantum numbers and spectrum. We denote by $[q_1 q_2]$ the fully antisymmetric state of the two quarks q_1 and q_2 . The composition of the members of the nonet is as follows:

$$\begin{aligned}
 a^+(I=1, I_3=+1, S=0) &= [su][\bar{s}\bar{d}] \\
 a^0(I=1, I_3=0, S=0) &= \frac{1}{\sqrt{2}} ([su][\bar{s}\bar{u}] - [sd][\bar{s}\bar{d}]) \\
 a^-(I=1, I_3=-1, S=0) &= [sd][\bar{s}\bar{u}] \\
 f_0(I=0, S=0) &= \frac{1}{\sqrt{2}} ([su][\bar{s}\bar{u}] + [sd][\bar{s}\bar{d}]) \\
 \sigma_0(I=0, S=0) &= [ud][\bar{u}\bar{d}]
 \end{aligned}$$

$$\begin{aligned}
\kappa(I = 1/2, I_3 = +1/2, S = +1) &= [ud][\bar{s}\bar{d}] \\
\kappa(I = 1/2, I_3 = -1/2, S = +1) &= [ud][\bar{s}\bar{u}] \\
\kappa(I = 1/2, I_3 = +1/2, S = -1) &= [us][\bar{d}\bar{u}] \\
\kappa(I = 1/2, I_3 = -1/2, S = -1) &= [ds][\bar{d}\bar{u}]
\end{aligned}$$

where the neutral states $f(980)$ and $\sigma(450)$ are superpositions of the isoscalar states f_0 and σ_0 . The mixing angle results to be small because the OZI rule is respected in the physical mass spectrum.

In the limit of exact octet symmetry, the states given above are mass eigenstates, the mass matrix parameterized by α and β , the diquark masses squared with strange and non-strange content. In the most general case of octet symmetry breaking, two more parameters are required to account for symmetry breaking terms [4].

The mass spectrum obtained is inverted with respect to what one would get for a $q\bar{q}$ nonet: the isolated $I = 0$ state is the lightest one and strange particles come next. The same pattern is shown by data and this is a most evident indication in favor of the four-quark nature of the scalar nonet.

Strong decays. Diquarks, being colored objects, cannot be separated by their anti-particles. As soon as the distance between two diquarks in a four-quark state gets large enough, a $q - \bar{q}$ pair is created out of the vacuum and the state should dissociate into a baryon-antibaryon pair. This process is obviously kinematically forbidden as long as four-quark light scalars are considered.

An alternative decay mechanism is the switching of a quark-antiquark pair between the two diquarks to form a pair of color neutral $q\bar{q}$ states (pseudoscalar mesons), which can indefinitely separate from each other. In the exact $SU(3)$ limit there is only one amplitude, \mathcal{A} , to describe this process. The amplitude \mathcal{A} describes the tunneling from the bound diquark pair configuration to the meson-meson pair, made by the unbound final state particles. As seen in Ref. [4], the value $\mathcal{A} = 2.6 \text{ GeV}$ gives a good description of the rates, compared to the available experimental information. The large value of \mathcal{A} seems indicative of a short distance effect, making perhaps more justifiable the use of flavor $SU(3)$ symmetry.

Our picture has some connection with baryonium states [9] and with the $K\bar{K}$ molecule picture [2]. In the latter case, however, the analogy is only superficial.

Adding the other three $SU(3)$ allowed (annihilation-)couplings (neglecting a fourth coupling related to a pure singlet-to-singlets amplitude) improves the description of the OZI allowed channels, except for the κ width, which seems to be sensibly smaller than the observed one. Also the OZI forbidden decay $f \rightarrow \pi\pi$, turns out to be too small with respect to the experimental rate, even allowing for the full $SU(3)$ effective strong decay Lagrangian. It is quite possible that this mode proceeds via a different mechanism.

However the overall picture is encouraging and reinforces considerably the case of the scalar mesons as $(q)^2(\bar{q})^2$ states.

Open and hidden charm mesons. A natural extension of the present scheme is the existence of analogous states where one or more quarks are replaced by charm or beauty. We consider the case of charm, extension to beauty is obvious. Open charm scalar

mesons of the form $S = [cq][\bar{q}\bar{q}]$, fall into characteristic $\mathbf{6} \oplus \bar{\mathbf{3}}$ multiplets of $SU(3)_f$. The $\bar{\mathbf{3}}$ has the same conserved quantum numbers of $c\bar{q}$ states ('cryptoexotic'), but the $\mathbf{6}$ has a pure exotic content. Hidden charm states of the form $[cq][\bar{c}\bar{q}]$ fall into $\mathbf{8} \oplus \mathbf{1}$ multiplets of $SU(3)$. In Ref. [4] a list of possible decays and related thresholds has been given.

Two issues are crucial to the description of open or hidden charm four-quark mesons: *isospin breaking* and *heavy-quark spin symmetry*. These aspects are briefly summarized in the next two paragraphs.

The mesons $a(980)$ and $f(980)$ are degenerate within about 10 MeV [10]. This reflects the smallness of the OZI violating contributions (annihilation graphs) to the mass matrix, which would align the mass eigenstates to pure $SU(3)$ representations. Thus sizeable deviations from the isospin basis are expected. Due to asymptotic freedom, suppressing quark pair annihilation into gluons, we expect annihilation contributions to be even smaller in systems containing heavy quarks. The mass eigenvalues will be aligned with states diagonal with respect to quark masses, even for the light, up and down, quarks [9]. The $D_{sJ}(2632)$ [11], if confirmed, could be interpreted as a $[cd][\bar{d}\bar{s}]$ state, not an isospin eigenstate [12], whose decay into $D^0 K^+$ is OZI forbidden [8].

The approximate spin-independence of heavy quark interactions, which is exact in the limit of infinite charm mass, implies both spin zero and spin one diquarks to form bound states. This implies a rich spectrum of states with $J = 0, 1, 2$. The states with $J^{PC} = 1^{++}$ and 2^{++} could be identified [13] with the $X(3872)$ and $X(3940)$ seen in BELLE data [14].

Also for these states isospin breaking would apply. An indication of the latter phenomenon comes from the observation of the relative decay rate of $X \rightarrow J/\psi + \rho$ and $X \rightarrow J/\psi + \omega$.

Heavy-light diquarks can be the building blocks of a rich spectrum of states which can accommodate some of the newly observed charmonium-like resonances not fitting a pure $c\bar{c}$ assignment. A new charm spectroscopy could be behind the corner.

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REFERENCES

1. F.E. Close and N.A. Tornqvist, J. Phys. **G28** (2002) R249 and references therein.
2. J. Weinstein and N. Isgur, Phys. Rev. Lett. **48** (1982) 659.
3. R.L. Jaffe, Phys. Rev. **D15** (1977) 281; hep-ph/0001123.
4. L. Maiani, F. Piccinini, A.D. Polosa and V. Riquer, Phys. Rev. Lett. **93**, 212002 (2004).
5. R.L. Jaffe and F. Wilczek, Phys. Rev. Lett. **91** (2003) 232003.
6. KLOE Collaboration (A. Aloisio et al.), Phys. Lett. **B537** (2002) 21; E.M. Aitala et al., Phys. Rev. Lett. **86** (2001) 770.
7. E.M. Aitala et al., Phys. Rev. Lett. **89** (2002) 121801.
8. G. Zweig, CERN report S419/TH412 (1964), unpublished; S. Okubo, Phys. Lett. **5**(1963) 165; I. Iizuka, K. Okuda and O. Shito, Prog. Theor. Phys. **35** (1966) 1061.
9. G.C. Rossi and G. Veneziano, Nucl. Phys. **B123** (1977) 507; for a recent update see [arXiv:hep-th/0404262].
10. S. Eidelman et al., Phys. Lett. **B592** (2004) 1.
11. A.V. Evdokimov et al., [arXiv:hep-ex/0406045].
12. L. Maiani, F. Piccinini, A.D. Polosa and V. Riquer, Phys. Rev. **D70** (2004) 054009.
13. L. Maiani, F. Piccinini, A.D. Polosa and V. Riquer, [arXiv:hep-ph/0412098].
14. K. Abe et al., [arXiv:hep-ex/0408116].